**SKI-INSITE TRD-06-04**

**INSITE reporting**

# INSITE Document

# Review of supraregional modeling of groundwater flow in eastern Småland SKB R-06-64

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**INSITE (INdependent Site Investigation Tracking & Evaluation)**

**is SKI's advisory group on site investigation issues**

Review of:

SKB R-06-64: Storregional grundvattenmodellering – fördjupad analys av flödesförhållanden i östra Småland: Jämförelse av olika konceptuella beskrivningar [Large-regional groundwater modelling – a deepened analysis of the flow situation in eastern Småland: Comparison of different conceptual descriptions]. Lars O. Ericsson, Johan Holmén, Ingvar Rhén, and Niklas Blomquist, May 2006 (in Swedish, with a summary in English).

Review by Joel Geier for SKI/INSITE.

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**Introduction:**

The subject of this review is a report on regional hydrogeologic modelling and related analyses performed by the Swedish Nuclear Fuel and Waste Management Co. (SKB) as a continued contribution to a discussion on the significance of areas of regional-scale groundwater recharge for repository location. From basic principles of hydrology, such areas are usually expected to be located well inland of the present-day coastline.

The suggestion for this siting concept was initially raised in the report of a study commissioned by the Swedish Nuclear Power Inspectorate (SKI) and published in November 2001 (Voss and Provost, SKI-01:44), which indicated, based on relatively simple groundwater models, that such sites could have advantages in terms of long and/or slow pathways resulting in long return times to the biosphere for the radionuclides released from the repository into the geosphere. The Swedish authorities' evaluation of SKB's integrated plans for selection of sites for further investigation (SKB, 2000; Miljödepartment 2001) included a requirement that SKB should clarify its assessment of recharge and discharge areas, and of the depth at which saline groundwater is encountered, as factors in the siting process.

Also in November 2001, SKB received permission from the Swedish environmental ministry to prioritise three coastal sites, Forsmark, Tierp north and Simpevarp, for preliminary site investigations, conditional on further resolution of hydrogeologic issues for an inland site, Hultsfred. After subsequent modelling work by SKB (reviewed in INSITE TRD 04-14), the topic was looked at again by its original proponents in review work carried out for the Swedish Radiation Protection Authority (SSI), which issued a statement on the issue in September 2004 (Dverstorp and Wiebert, 2004).

The most recent report by SKB, R-06-64, is intended to address criticisms of their earlier studies, as set forth in reviews by INSITE, SKI, SSI, and stakeholder groups. In the meantime, SKB has completed the initial stage of site investigations at Forsmark and Simpevarp (including sub-areas Laxemar and Simpevarp), presented preliminary safety evaluations for these sites based on simplified criteria that SKB proposed earlier in the process, and is now proceeding with the final planned phase of above-ground investigations (referred to as the "complete site investigation" phase) at both Forsmark and Laxemar.

The INSITE review group was formed to review and provide advice to SKI on the site investigations at SKB's two chosen sites, Forsmark and Simpevarp. Although the mandate of INSITE does not include review of the strategy and decisions underlying the preceding site-selection stage of the Swedish repository programme, the regional hydrogeological situation is one of the major elements in the characterization of any site, and is consequently of relevance to INSITE's work. For example, information on regional hydrogeology is needed in order to demonstrate overall system understanding, as well as to identify the range of possible future conditions for engineered barriers and to bound the potential for geosphere migration of radionuclides. Assumptions about regional groundwater flow may also play an important role in decisions that affect site investigations, such as choosing locations for boreholes to characterise effective boundary conditions for the candidate site.

With this background, INSITE has reviewed SKB's work on regional flow from the perspective of its significance for site understanding and site characterisation. While some comments may coincidentally be pertinent to discussions of the recharge-area siting concept, it should be understood that evaluation of that concept has not been an aim of this review.

**Previous Documents Relevant to this Review**

The report considered in this review presents the latest phase of SKB's regional-scale groundwater modelling which was initiated to address questions raised during the siting stage, regarding the possible use of regional groundwater flow and salinity as factors in choosing the best candidate site for a deep repository.

Significant background papers and reports for this series of reports include:

> Leijon, B. *Nord-syd/Kust-inland: Generella skillnader I förutsättningar för likalisering av djupförvar mellan olika delar av Sverige* [North-south/Coast-inland: General differences in conditions for siting of a deep repository among different parts of Sweden]. SKB R-98-16, Swedish Nuclear Fuel and Waste Management Co., Stockholm, 1998.
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> Tóth, J. and Sheng, G. Enhancing safety of nuclear waste disposal by exploiting regional groundwater flow: The recharge area concept. *Hydrogeology Journal*, Vol. 4, No. 4, 1996.
>
> Voss, C.I. and Provost, A.M. Recharge-area nuclear waste repository in Southeastern Sweden: Demonstration of hydrogeologic siting concepts and techniques. SKI Report 01:44, Swedish Nuclear Power Inspectorate, Stockholm, 2001 (in English).
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> SKB, 2003. Grundvattnets regionala flödesmönster och sammansättning – betydelse för lokalisering av djupförvaret [Regional groundwater flow patterns and composition --implications for siting of a deep repository]. SKB Report R-03-01, March 2003 (in Swedish).
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> Follin, S. and Svensson, U. On the role of mesh discretisation and salinity for the occurrence of local flow cells: Results from a regional-scale groundwater flow model of Östra Götaland. SKB Report R-03-23, June 2003 (in English).
>
> Holmén, J.G., Stigsson, M., Marsic, N., and Gylling, B. Modelling of groundwater flow and flow paths for a large regional domain in northeast Uppland: A three-dimensional, mathematical modelling of groundwater flows and flow paths on a super-regional scale for different complexity levels of the flow domain," SKB Report R-03-24: ", December 2003 (in English).
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> Dverstorp, B., and Wiebert, A., SSI:s synpunkter på SKB:s redovisning av grundvattnets regionala flödesmönster och sammansättning, och deras betydelse för lokalisering av ett slutförvar [SSI's comments on SKB's account of regional groundwater flow patterns and composition, and their implications for siting of a final repository]. SSI Project Memorandum 2004-08-30, Swedish Radiation Protection Authority, August 2004 (in Swedish).
>
> SKI-INSITE Core Group. SKI-INSITE Technical Review Document TRD-04-14, September 2004.

Also taken into consideration for this review are discussions at SKB's Expert Meeting on Regional Flow Modelling, which was convened in Stockholm, 23 April 2004, and the presentation and discussion of SKB's most recent modelling work at the SKB/SKI/SSI/INSITE/OVERSITE/SIERG meeting in Figeholm, 14 June 2006. The former meeting featured presentations of the modelling behind SKB reports R-03-23 and R-03-24, as well as more recent modelling results presented by Clifford Voss. The latter meeting included a presentation of the modelling results and discussion of questions posed by INSITE and OVERSITE members.

The report by Leijon (1998) is an earlier survey of the issues covered in R-03-01. The SKI report by Voss and Provost (2001), hereafter referred to as Voss & Provost, served to stimulate SKB's modelling as presented in the present reports. The paper by Tóth and Sheng (1996) set forth the recharge-area siting concept in the context of a hypothetical repository located in the Canadian Shield.

SKB's report R-03-01 is expressly intended to directly address the requirement by the Swedish authorities that SKB should develop a better basis for assessment of recharge and discharge areas and of the depth at which saline groundwater is encountered, as factors in the siting process. The document was aimed (1) to document and discuss processes of significance for groundwater circulation and salinity distribution in the Swedish bedrock, and (2) to assess the distribution of recharge and discharge areas along with the depth at which high salinities are encountered, as geoscientific indicators of [site] suitability. The reports R-03-23 and R-03-24 are background reports to R-03-01, giving details of groundwater flow modelling which was carried out for northern Uppland (including Forsmark) and eastern Götaland (including Simpevarp and Laxemar). INSITE TRD 04-14 gives a review of these three reports.

**Overview of Report Contents**

The report presents hydrogeological models for an approximately 150 km x 60 km region of eastern Småland, including Oskarshamn, coastal waters, and inland areas. The major aim of the study is to analyse groundwater flow patterns at this supraregional scale, especially with respect to recharge and discharge, *i.e.* upflowing or downflowing groundwater movements and paths towards discharge from a repository at 500 m depth. The work considers sensitivity to depth dependency, anisotropy, and heterogeneity of hydraulic conductivity (*K*), as well as the role of deformation zones and groundwater salinity (affecting density-dependent flow).

The work is essentially a series of variations on a model that includes detailed topography as well as regional-scale geological features including lithologic variation, deformation zones, and simplistic models of heterogeneity on finer scales. These are compared in terms of percentile statistics for transport path lengths, advective transport times, and specific flow (Darcy flux) for nonreactive solute emanating from hypothetical repository locations at 500 m depth throughout the region, as well as a measure (Rp) of whether the vertical component of flow through the hypothetical repository horizon is predominantly downward or upward. Sites within the region are compared based on these measures, and also based on whether they are robust with respect to a range of variations in the geological system properties.

The project team is identified as Lars O. Ericsson (project leader), Johan Holmén, Ingvar Rhén, Niklas Blomkvist, and Jan-Olof Selroos.

The models cover an irregularly shaped region approximately 150 km x 60 km, with boundaries based on surface water divides and extending from Nässjö in the west to about 10 km offshore of Äspö in the east. The model region consists of the watersheds of three major streams (Emån, Virån, and Marströmmen) plus smaller streams draining directly to the coast around Äspö, Kråkemåla and Oskarshamn.

The topography is based on the Swedish National Survey's digital elevation database on a 50 m grid scale. Bathymetry for the offshore portions is a mix of high-resolution digital data from special surveys for the Oskarshamn-area site investigations, combined with bathymetry obtained by digitization and processing of standard nautical charts for other areas. These data are represented in the model at a resolution which varies from 100 m to 200 m depending on the calculation grid as described in Section 4.2.

Flow was modelled to a depth of 2.5 km, which was justified by exploratory simulations.

The model accounts for variation of soil thickness, glaciofluvial and moraine sediments, and lateral variation of bedrock geology within the model, based on regional-scale mapping by the Swedish Geological Survey (SGU). Stratigraphy of sedimentary (Almesåkra group) deposits cut by surficial diabase/dolerite dykes in the westernmost part of the model is represented in a simplified way. These various units are treated as having different mean hydraulic conductivities in the model, based on data available from SGU's well archives.

Regional-scale lineaments (interpreted as vertical deformation zones) are taken into account in certain variational cases. The base map for these lineaments has a mean spacing between lineaments of roughly 5 to 8 km, forming what appears to be a sparsely connected network, with blocks of up to 20 km without presence of lineaments. A predominantly north-south family of diabase/dolerite dykes is also accounted for in some variational cases; these have a mean spacing on the order of 20 km and do not form a connected network.

Flow calculations are performed using DarcyTools, which uses a continuum representation and accounts for density-dependent flow coupled with advective-dispersive transport of dissolved salt. Approximately 30 different calculation cases were performed, representing various combinations of variations from a reference case (Case 5) which is based on the following:

- Detailed (50 m scale) topography and bathymetry.
- Spatially varying lithology based on SGU mapping data.
- Depth-dependent hydraulic conductivity (constant from 0 to 67 m depth, then decreasing in inverse proportion to approximately the square of the depth ($d^{2.02}$) for $d > 67$ m; this is based on SKB's data from the Oskarshamn site ).
- Regional-scale deformation zones with depth-dependent hydraulic conductivity (similar to that in the rest of the model, except that K decreases in inverse proportion to $d^{1.783}$ rather than $d^{2.02}$ for $d > 67$ m).
- Diabase/dolerite dykes which are assumed to have higher K along the length of the dykes (versus transverse), by a factor of 100, and which have K decreasing by the same function of depth used for the regional-scale deformation zones.
- Variable depth of quarternary deposits (moraine, and glaciofluvial) based on SGU maps.
- Fresh water throughout model.
- Steady-state flow.

Variations with respect to this reference case include:

- Various idealized, simplistic cases for comparison, including inclined plane instead of actual topography; homogeneous bedrock with and without horizontal anisotropy and depth-dependence in K, including a set of saline/density-dependent simulations for one such case.
- Increased anisotropy in diabase/dolerite dykes (by factors of 1000 and 10000).
- Horizontal anisotropy (K higher by factor of 10 in horizontal directions vs. vertical direction).
- Diabase/dolerite dykes and regional deformation zones excluded in different combinations.

- Increased K in deformation zones (by a factor of 10).

- Sensitivity cases in which the water table deviates from the surface by up to 5 m in recharge areas using an ad hoc smoothing algorithm (Case 5J).

- Saline/density-dependent transient flow (two different assumptions for initial conditions).

- Additional, stochastically generated horizontal deformation zones (circular, with P32 intensity of 3.7e-4 corresponding to a mean vertical spacing of about 3 km). A “negative spatial correlation” (not described in mathematical terms) is used to avoid having these too close to each other. The diameters of the horizontal zones are based on sampling of the sample c.d.f. for surficial regional lineaments (assumed by the modellers to correspond to subvertical deformation zones). Two different realizations of this model were tested as separate variants.

- Saline/density-dependent transient flow for the preceding variant (second realization and second assumption for initial conditions).

- Stochastic variation in block-scale conductivity superposed on depth-dependent K field (two realizations). The form of stochastic variation is a simple lognormal random field for K with no spatial correlation beyond the scale of the grid blocks (which varies from 100 m to 800 m depending on depth as described in Section 4.2). This is described in the text as a “stochastic continuum” but it is the most simple conceivable version of that approach, not a full geostatistical approach which might be expected from a cursory reading.

- Saline/density-dependent transient flow for the preceding variant (first realization and second assumption for initial conditions, plus an additional assumption for initial conditions).

- Stochastic variation in K according to the lognormal random model, but with factor-of-10 horizontal anisotropy.

- Same as preceding case but with depth-dependent horizontal anisotropy ($K_h = f(d)*K_z$ with $f(d) = 10$ for $d<200$ m; $f(d) = 1$ for $d>400$, and decreasing linearly from $d = 200$ m to 400 m. In other words, same as the previous case but with anisotropy factor decreasing with depth from 200 m to 400 m and isotropic condition for $d>400$ m.

The three different initial conditions considered for the saline/density-dependent cases were:

- Case s1: Freshwater to 500 m below sea level, and thenceforth a uniform linear increase of initial salinity with depth to 10% salinity at the base of model (-2500 m).

- Cases s2 and s3: Initial salinity is related to topography (amplified by a factor of 5.385) except for elevations < 100 m where the equisalinity lines are at constant depth.

Results of these variations are compared in terms of percentile statistics for a population of hypothetical, 1 $km^2$ “repositories” placed at 500 m depth:

- Advective transport path length, L;
- Advective transport time, t;
- Specific flow, q;

Flow direction, Rp (the percentage of area within a hypothetical repository at 500 m where the vertical component of groundwater flux is locally downward)

In addition, the population of hypothetical “repository areas” are evaluated by the following series of tests (where the symbol "1" is used to denote the logical intersection of sets, *i.e.* areas that are included for both criteria on either side of the symbol):

| | |
|---|---|
| Test 1A | (1000 areas with longest *L*) 1 (1000 areas with longest *t*) 1 (1000 areas with lowest *q*) |
| Test 1B | (1000 areas with longest *L*) 1 (1000 areas with longest *t*) |
| Test 1C | (1000 areas with longest *L*) 1 (1000 areas with longest *t*) 1 (Rp > 90%) |
| Test RA | Locales with Rp > 90% for all cases in a series of calculation cases with different properties. |
| Test RB1 | Locales passing Test RA and also with transport times among the 20% longest times. |
| Test RB2 | Locales passing Test RB1 and also with q < 0.5 mm/year and L > 1.5 km. |
| Test P1 | Locales which are among the 1000 longest t and 1000 longest L for a series of calculation cases. |
| Test P2 | Locales which are among the 1000 longest t and 1000 lowest q for a series of calculation cases. |
| Test P3 | Locales which are among the 1000 longest t, 1000 lowest q, and 1000 longest L for a series of calculation cases. |

The main conclusions reached according to the authors are:

- The factor of greatest importance for regional flow conditions at repository depth of 500 m is topography. Topography is found to be of greater importance than the conductivity field, including effects of different lithological units, regional deformation zones, local heterogeneity and

Quaternary deposits.

- Groundwater in the rock volume analyzed can be described as primarily dominated by local flow cells, with mean path lengths on the order of 2 km and only a very small fraction of "supra-regional" paths less than 10 km.
- Decreasing K with depth leads to smaller flow cells.
- Anisotropy with Kh > Kz leads to larger flow cells and longer flow paths.
- Anisotropy with Kz > Kh leads to smaller flow cells and shorter flow paths.
- Variation of K with depth and anisotropy with Kh > Kz, have a greater effect on the flow pattern than the lithological units, deformation zones, dolerite dykes, and Quaternary deposits.
- Dolerite dykes and deformation zones affect local flow patterns but are of little importance for the regional pattern.
- "Supra-regional" horizontal deformation zones do not significantly affect the large-scale flow pattern.
- Introducing local heterogeneity does not change the general flow pattern, but increases flow path lengths and breakthrough times by about 30%.
- Density effects have little importance in the model region except very near the coast.
- Hypothetical inland repository locations do not have generally longer breakthrough times, longer discharge path lengths, or smaller specific flows than coastal repository sites.

A general conclusion reached by the authors is that increased model complexity leads to an increased tendency toward the development of more local flow cells.

**Major Comments**

The project accomplishes its major aim of analysing groundwater flow patterns at the supraregional scale with respect to recharge and discharge, and its sensitivity to regional-scale patterns of hydraulic conductivity, within the limitations arising from the simplifications and assumptions. This work is a significant improvement over SKB's previous modelling work on this topic in several respects:

- The level of analysis for eastern Småland (containing Laxemar) is brought up to a similar level of detail as previous work for northern Uppland (containing Forsmark), so SKB's ongoing site investigations at the two sites can now draw on comparable supraregional models.

- Several questions raised in previous reviews, regarding the role of geologic complexity and depth-dependence of hydrogeologic properties including anisotropy, have been addressed at least in a limited way.

- SKB seems to have heeded prior comments that variations in assumptions regarding hydrogeologic complexity should be compared with a reasonably realistic reference case, rather than with an overly simplified case that could be regarded as highly improbable.

- With the tests P1-P3, SKB has also taken up the comment from the authorities that it is more meaningful to look at sites that are robust in the sense that they give adequate safety function (in terms of the measures *L*, *t*, and *q*) for a variety of plausible models of the geologic properties at depth.

- An improved grid resolution is used in the vertical direction (vs. the previous study documented in R-03-23), so the vertical resolution is now closer to that in the horizontal directions.

- The chosen depth for the model's lower boundary of 2500 m was tested by a sensitivity analysis (Section 6.7), which seems to be a response to review comments on the previous studies. The comparison is given only in terms of cumulative distributions for L, T and q for paths passing through the repository horizon of 500 m, for which differences do appear to be inconsequential.

The first four chapters of the report which describe the methodology and data support are clearly written. For the most part mathematical details necessary for evaluating the work are presented in adequate detail (with some exceptions as noted below).

The work presented in this report has at least partly addressed the following concerns that were raised in INSITE TRD 04-14:

- Anisotropy and elevated hydraulic conductivity in the shallow (< 100 m deep) bedrock,-Conductive subhorizontal fracture zones below repository depth,

- Differences in near-surface permeability due to differences in sediment cover between upcast and downcast regional blocks, or along tilted regional blocks.

- Certain other forms of heterogeneity in the bedrock (lithologic variations and dyke swarms which could correlate to permeability).

Concerns raised in INSITE TRD 04-14 which were not addressed include:

- Subvertical fracture zones on scales smaller than the major, regional-scale lineaments that divide the rock into blocks on a 5-10 km spacing.

- Inclined fracture zones.

Section 7.7, which presents results of tests of different hypothetical ‘repository locations’ for robustness with respect to variation in geological assumptions, is a significant development for the siting issue which originally motivated this work. The hypothetical locations that pass these tests (P1, P2 and P3) are uniformly 15 km or more inland from the present-day coastline, and are scattered as far inland as the western boundary of the model, in the case of Test P1 which is based on long discharge path lengths and transport times (see Figures 7-22 and 7-23). Test P2, which is based on long transport times in combination with low specific flow, favours three sites which are in a band roughly 15 to 30 km inland; all three of these locations are situated on regional topographic divides internal to the model, which are presumably recharge areas.

The most stringent test, P3, which requires robustness with regard to all three criteria, yields just one location, which is situated on a regional triple divide, 15 km inland. This location is robust with respect to one suite of variants (Series 2, defined in Table 7-1) but not a second suite (Series 4) which includes stochastic variation of block *K* values (one particular realization). No statistics are given for the performance of this location in the latter case. The report simply states (Section 7.7.4.2) that no locations passed this test for the second suite of variants, which implies that the triple-divide location was not among the 1000 best locations in terms of each of the measures *L*, *t*, and *q*.

The general conclusions are approximately those reached from previous SKB modelling studies (R-03-23 and R-03-24), with minor refinements mainly relating to the more detailed aspects of heterogeneity that have been considered here.

Although the work presented in this report is substantial, it also has significant limitations which should be kept in mind in applying the conclusions that the authors draw. The following limitations can be noted (and are discussed in further detail in the section, “Detailed Comments”).

- The models are extrapolative and have not been checked against independent field measurement . Appropriate data for calibrating and testing such large-scale models are certainly difficult to obtain, but some possibilities are discussed in the detailed comments below.

- Comparisons between variants are based mainly on lumped statistics calculated over the whole model area, which give limited insight into flow fields and may not discriminate well among the ‘better’ performing sites.

- The *F* measure of geosphere barrier potential is not used for comparisons, despite SKB’s earlier assertion that this is more meaningful than considering discharge path length *L*, advective transport time *t*, and specific flow (Darcy flux) *q* as independent measures of site suitability.

- The usefulness of the *Rp* statistic (the percentage of area within a hypothetical repository site where the vertical component of groundwater flux is locally downward at the 500 m level) which is used in some tests is still not clear.

- Most of the tests applied to identify better-performing hypothetical repository locations are based on an ordered ranking of potential locations, rather than satisfying fixed thresholds that are clearly related to safety.

- Although plots of flow fields were added to the report in response to review comments on an earlier version (and these are somewhat helpful), they are still inadequate for understanding the effect of different variants on flow fields and groundwater heads (*i.e.* pressure) at and near the repository depth, and for estimating the likely effects of variations which go beyond the narrow range that has been analyzed.

- The heterogeneous boundary condition at the upper surface (due to topography) contrasts with a much more uniform boundary condition along the vertical edges of the model (regular decay of head with depth); plots to show the significance of this contrast are not presented.

- The importance of different scales of topographic undulation has not been addressed in a rigorously quantitative manner, so statements about the importance of “local topography” or “topographic undulation” relative to other factors must be taken as qualitative.

- Treatment of subhorizontal and inclined deformation zones is extremely simplified and only weakly supported by the data.

The conclusions regarding the influence of geologic heterogeneity of various forms are somewhat overstated, considering that the range of possibilities explored is still small:

- Structured heterogeneity at a scale below that of regional lineaments has not been considered. The “heterogeneous” calculation cases use a model which can be described in geostatistical terms as “pure nugget effect,” *i.e.* with no spatial correlation, superposed on a trend in the geometric mean value with depth. Lineaments representing bedrock structures on the 0.5 to 10 km scale have not been considered, despite the fact that flow path statistics are evaluated predominantly on that scale.

- Regional variation in the structural pattern is not considered. Since variants that consider the effects of regional-scale structures are compared with the reference case mainly in terms of lumped statistics, effects in portions of the area where the regional lineaments form a more coherent network may be suppressed or diluted.

- The treatment of anisotropy and its likely depth-dependence is limited. This may affect the assessment of the depths to which localised topography-controlled cells can penetrate. It is well-known that the regional stress field has an influence on rock mass permeability, and anisotropy in the stress field in combination with stress-dependent changes in fracture aperture causes an increase in anisotropy of the flow field (Min *et al*., 2004).

- The method for evaluating a depressed water table in the highest-elevation areas, due to hill-slope drainage effects, is not clearly explained; the results obtained may contradict past SKB results regarding the importance of high-resolution topography, and should be better explained in this regard.

The work assumes that deformation zones (vertical and horizontal) are internally-connected transmissive features at the full vertical scale of the model, with regular variations of *K* in deformation zones and intervening rock. Thus the modelled flow path realisations are controlled primarily by deformation-zone geometry, isotropy-anisotropy variations, and heads distribution as imposed by topography. Given the assumed connectivity, the modelling suggests that recharge-to-discharge flow cells are influenced strongly by topography. SKB acknowledges this strong influence in their conclusions but its strong predominance could be due to the assumed regularity of the *K* field in the various cases.

Thus, while the results of this report can be seen as a useful extension of the quantitative state of understanding on these issues, they cannot be seen as definitive in most respects. If they are utilized as part of site-specific information in the license application for one of the two sites currently under consideration, further scrutiny of the assumptions is warranted.

In the context of site characterization, several issues raised by INSITE in TRD 04-14 are not addressed and/or are outside the scope of this report:

- *Origins and evolution of salinity as originating from multiple distinct waters (deep shield brines, palaeo-Baltic Sea, Litorina, and modern Baltic waters).* These have implications for initial and boundary conditions as well as any submodel for salinity generation within the modelled volume. In the present study, density-dependent flow was judged to be unimportant "except near the coast." Reliance primarily on freshwater simulations was defended in the present study by comparison of bulk statistics over the whole model area, in which the significance of near-coast effects in effect were diluted.

- *Suitability of local surface water divides as boundaries for smaller regional-scale models*. In the present report, emphasis has been given to statistical measures of flow path length, breakthrough times, specific flux, and the *Rp* measure of "downward directedness of flow." The visualizations of flow fields are inadequate to assess the significance of

- local surface water divides as boundaries for smaller-scale models. Moreover, an artificial convergence of flow at constrictions along the edges of the presented model suggests that the prescribed no-flow conditions along the drainage divides forming the model boundaries may not be strictly correct (though unlikely to substantially affect the conclusions of this work as presented).

- *Sensitivity of salinity to local conditions*. If existing data on salinity at depth are judged to be inappropriate for calibrating or even checking this type of model (as suggested by the very brief statement about lack of suitable data for calibration in Section 3.10), then this bears out the previous INSITE comment that groundwater flow paths from repository depth to surface are dependent on site-dependent factors in ways that are not yet adequately understood or parameterised in models.

- *Importance of temporal changes for long-term performance of the repository*. While the present analysis has considered robustness with regard to uncertain assumptions about bedrock and Quaternary hydrologic parameters, and thus improves on SKB's previous work, INSITE's comment that future conditions also need to be considered has not been taken up. Considering that any releases from the engineered barriers are most likely to occur under future conditions which differ from the present-day, demonstration of robustness for a given site requires that reasonable models for future site evolution also be used as part of the evaluation.

These issues would need to be addressed by other parts of SKB's programme, particularly if results of the current SKB studies are used as site-specific information for license application.

## Detailed Comments

*Models not checked against field measurements*

The models are purely extrapolative. A great deal of geometric and geologic data have been used as input but there has been no calibration or comparison to hydrologic observations. When the question of calibration was raised by SSI in the first presentation of this work, the project manager Lars Ericsson responded that SKB have looked at geophysical methods for detecting the saltwater interface. However, this type of check does not appear in the report, nor are any other comparisons.

In our previous review on the subject of supraregional groundwater flow (INSITE TRD 04-14), we noted that SKB's previous models indicated that local factors of topography and hydrogeology have a strong influence on the occurrence of salinity, which was illustrated by an apparent unpredictability of how salinity varies with depth at a particular location. A question remains as to whether these types of models can predict observations of groundwater conditions (depth variations of salinity and heads, if they can be usefully measured), particularly when the likely transience of deep groundwater systems is taken into account.

The most feasible parameters for calibrating or checking such models include measurements of groundwater pressures, temperatures, salinities, and ages (from isotopic data).

Regarding groundwater pressures, to date SKB's site investigation programme has had difficulties obtaining first-strike (*i.e.* nominally undisturbed) measurements of pressures at depth with sufficient resolution to discriminate between flow models, especially in low-permeability rocks which are expected at greater depths.

Regarding temperature, infrared surveys to detect discharge areas based on thermal anomalies have previously been suggested by INSITE as a possible means of checking site-scale flow models.

Regarding salinities, the present report correctly makes the point that the model is dependent on what initial conditions are assumed for 10,000 years BP (Case sl in Fig 4-10 and Cases s2/s3 in Fig 4-11). The latter reflect some topographic influence on salinity distribution and are similar to the very large-scale concept shown in Fig 2-35 (note that the large-scale lateral flows indicated schematically in this figure are now discounted and also that the very deep freshwater-saline interface attributed to Gravberg is based on probably unreliable data).

The implication of salinity outputs from *e.g.* Cases 5s2, 8s2, 8s3 (see Fig 6-64) is that lateral heterogeneity of salinity over relatively small scales at >1000m depth would be consistent with these models which give the deep localised flow cells as shown in Fig 6-61. From the figures, it seems that detectable lateral heterogeneity of salinity (*i.e.* variation that would be distinguished by deep investigation boreholes with a reasonable level of confidence) should occur at the scale of 5-10 km or larger.

The model also suggests characteristic heterogeneity at the east side of the modelled section, near to the coast. The distribution of salinity in Laxemar boreholes is interesting in this respect. The corollary of this is that using salinity heterogeneity to test the model for inland locations would need to go deeper to find interpretable salinity increases. Of course, if inland boreholes were to find substantial salinity at much shallower depths, then this would discredit the deep freshwater flow lines shown in all of these model outputs (*e.g.* Fig 6-61).

Regarding groundwater age, modelled travel times from repository depth to surface are typically 1000-2000 years (median value, see Fig 6-63), range 100-10,000 years. Assuming 'symmetry' in recharge-to-discharge flow paths, this implies that waters in the discharging limbs of flow cells are expected to have typical ages of several thousand years. If isotopic measurements were used to test these modelled flow cells, the expectation would be that there might be distinctive isotopic characteristics:

- $^{18}O/^{16}O$ indicating that all "glacial" age water has been flushed,
- localised zones where upflowing waters have moderating lowered $^{14}C$ (*e.g.* 25 pmC),
- localised zones where downflowing waters have high $^{14}C$ (.*e.g.* 80-50 pmC) and maybe also "modern" $^{3}H$ contents.

Although the modelled flow paths (*e.g.* in Fig 6-61) are multiple realisations and therefore somewhat scattered, the inferred control of recharge and discharge locations by topography suggests that significant lateral heterogeneity in isotopic indicators of groundwater age, at the scale of 5-10 km, should be detectable in boreholes. As suggested above, the most practical test of at least some of these concepts may be provided by the heterogeneity that is apparent in data from the various Laxemar boreholes.

*Comparisons based on lumped statistics*

The evaluation depends heavily on percentile statistics for pathways passing through a fixed repository horizon at 500 m depth. In comparing between variants, results are lumped as c.d.f.s for the entire modelling region, which may not be sensitive to significant differences in flow fields. It would be more useful to examine what are the impacts for locations that appear to be "good" repository sites in the reference case, both by means of statistical measures and illustrations of the flow pattern through such sites.

*F measure not used*

Models are compared in terms of transport path length (L), advective transport time (t), and specific flow or Darcy flux (q), treating these as independent measures of site suitability. No comparisons are given in terms of the factor $F = a_r L/q$ (using some representative value of the wetted surface $a_r$ or simply a scaled value $F/a_r$). This is surprising given SKB's statements in response to Voss and Provost (2001) that only the integrated parameter $F$ counts, not the values of $L$, $t$ and $q$ which can be seen as components of $F$ (since $q = L/t * porosity$ for a path with constant properties).

It is understandable that SKB should present results for the parameters used by Voss and Provost (2001), for the sake of direct comparisons with previous work. However, it is hard to understand why SKB has not given comparisons of repository sites in terms of the most meaningful parameter for geosphere retardation. Use of this parameter would have simplified the analysis of results, which in the present report is muddled by the assortment of "tests" making use of these measures in various combinations.

*Usefulness of the Rp statistic not clear*

The usefulness of the *Rp* statistic (the percentage of area within a hypothetical repository site where the vertical component of groundwater flux is locally downward at the 500 m level) is still not clear. In cases where heterogeneity is included in the model, a single trajectory can include several reversals of the vertical component along its length. A significant correlation between this statistic and anything meaningful for repository safety has not been established. Plots in Section 7.6 appear to show some correlation between *Rp* and the other measures used (*L*, *t*, and *q*) at least for some percentile ranges, but do not make clear how *Rp* augments those other parameters as a safety measure. It is not clear if SKB proposes this as something that might be measured at a site, *e.g.* in deep boreholes, or if it is simply a statistic that is presented mainly because it is convenient to calculate.

*Tests are based on ranking of potential sites rather than fixed thresholds related to safety*

The "tests" of hypothetical repository locations based on membership in one or more set of the "1000 best" locations, in reference to a given parameter (*L*, *t*, *q*, or *Rp*). The exceptions are Tests RA1 and RB2 which include tests of whether a location meets some fixed threshold value of *q*, *L*, or *Rp*. Conceivably, a location which fails a test because it is ranked number 1001 in terms of *L*, but which might be ranked number 1 or 10 in terms of *t* and *q*, could be the best in terms of potential for geosphere retention. It is also conceivable, for example, that the first 1200 locations in terms of *L* might yield adequate far-field transport performance, but only the first 800 locations in terms of *q*. The use of a "best 1000" test relies on only a relative ranking with no clear implications for transport performance. It is, furthermore, not useable if an objective were to be to compare locations in two separate supraregional model areas (*e.g.* northern Uppland and eastern Småland).

Again, use of the *F* parameter as a single measure for comparison would have helped to clarify, especially as SKB has defined threshold values of *F* for assessing site suitability (Andersson *et al.*, 2000).

*Plots of flow fields are inadequate; no plots of groundwater pressure*

There are no illustrations of the variations of head (*i.e.* groundwater pressure) through the modelled volumes.

Some plots to illustrate the flow fields were added to the report after the need for such plots was pointed out in preliminary reviews of an initial draft of this report. Unfortunately the format of the plots provided (*e.g.* Figure 6-19 and 6-61) are not very helpful except in the cases of the most radical differences and idealized geometry (Figure 6-20).

In these quasi-3D plots (oblique projections of trajectories of random colours), in general it is not possible to follow individual paths from recharge area to discharge area since they pass through a dense tangle in the 100 m to 500 m depth range. There is no way to be sure of the Y coordinate of a given trajectory, and hence the Z coordinates are not certain. A simple 2-D projection into a vertical plane running E-W (parallel to the nominal regional hydraulic gradient), and/or showing a narrower slice through the model, would have been much more revealing regarding the crucial question of how local topography, in combination with the various geologic factors, influences flow cells that penetrate to repository depths.

Thus, these added plots do not meet the need that was pointed out in review of the preliminary draft. This is important because, for most categories of system properties, only one or two variants are presented and more extreme cases might be envisioned (as even more realistic than the chosen variants, in some cases). With more quantitatively useable plots of the flow fields, it would be possible for a reviewer to estimate the impact of some of these cases, but with the presented plots this is not possible.

*Heterogeneous boundary condition at surface contrasts with vertical edges of the model*

The heterogeneous boundary condition at the upper surface (reflecting the topography at 50 m resolution) contrasts with an assumed regular decay of head with depth on the vertical edges of the model (except in the saline cases). In other words, the resolution at the top boundary of the model has a greater influence in the modelled flow than the resolution of permeability variation at the vertical edges of the model.

This might influence the outcome of the modelling, especially regarding conclusions about the strong influence of topography. The modelling does not show how the heads vary with the present model assumptions or how the flow paths would change if heads distribution on the edges were not regular.

Factors that might influence decay of topographic head with depth include smaller-scale deformation zones and heterogeneity within and/or irregular connectivity among the regional-scale deformation zones. Presumably an irregular distribution of head, if this could be imposed on the model edges with large-scale regularity as modelled, would just distort the flow lines but not make any substantial differences unless the general anisotropy also changed.

*Imprecise treatment of different scales of topographic undulation*

The report contains various statements about the importance of “local topography” or “topographic undulation” vs. other system properties, but what is meant by these terms is not defined with precision. A spectral decomposition of the topography in the region might have allowed definition and evaluation of these terms in a more rigorous manner. An analytical solution is available for the homogeneous case (Wörman et al., 2006) and could be used to resolve the significance of topographic undulation over different scales, as well as for verification of the DarcyTools numerical code for this type of application.

Even using a purely numerical approach (which is necessary for the heterogeneous case, at least with current analytical solutions), the role of topography on different scales could have been better elucidated by constructing models which have certain ranges of the topographic spectrum filtered out. The present report presents just the extreme cases of an inclined plane and natural topography at the full resolution of the digital database, plus one case with a form of smoothing which is intended to represent hill-slope drainage.

*Structured heterogeneity at scale below regional lineaments has not been considered*

The simulation model used to evaluate effects of heterogeneity in some variants, as set forth in Appendix 3, is just a lognormal random field of block-scale K values, without spatial correlation (apart from that due to the superimposed trend with depth in some cases). Thus, in geostatistical terms a pure nugget-effect model has been assumed. No geostatistical analysis of the regional well data is presented which would show if this model is valid, or if a model with non-zero correlation range would be more representative.

Since the scale of evaluation of “regional flow patterns” is large relative to the block scale, presumably an REV for this type of unstructured random field is reached. Hence it is not surprising that the calculated results differ only slightly from the reference case, mainly with just minor tortuosity effects for the statistics L and t and additional variability for q, which might have been predicted from stochastic continuum theory.

No account is taken of lineaments (assumed to represent deformation zones) on a scale smaller than the regional scale (10 km or larger, see Figure 4-15). There are large intervening blocks up to the 20 km scale or more, within which no structures are present. Site investigations in Fennoscandian bedrock have generally shown that many more lineaments are found when analyses are undertaken at smaller scales and/or using higher resolution databases. Thus only a limited sample of the regional structural fabric is likely accounted for. There is still a significant range of scales over which structurally-based heterogeneity of the bedrock is not accounted for, including most of the range of scales (0.5 km to 10 km) of transport paths for which results are presented.

*Regional variation in the structural pattern is not considered*

The interpreted regional lineaments are weakly connected across most of the southern two-thirds of the model. Such a poorly connected network of structures can be expected to have less influence on regional flow patterns than a more densely connected network. However, the analysis of results lumps results from the entire region together, and thus dilutes any effect that might be seen by analysis of the portion of the model with a more well-connected structural grid.

The lineament pattern used in the model is a "local pattern" based on structures mapped inside the modelled area. More regional studies reveal that there are large-scale breaks in landforms (Lidmar-Bergström, 1991) trending north-south and forming large scale steps which outline  regional rock blocks. One of these N-S structures is located approximately at Y= 1500 500 (RAK) and transects the area, but does not appear among the lineaments used as the basis for defining regional deformation zones in the model (Figure 2-14).

*Treatment of subhorizontal and inclined deformation zones is extremely simplified*

In the variant with “horizontal deformation zones,” disks representing a population of such zones are randomly located without any structural relationship to the (assumed) vertical regional deformation zones. Furthermore, to avoid overlaps they are anticorrelated in space (the form of the anticorrelation is not specified), which must reduce the chance that two could line up to make a longer high-*K* path through the bedrock.  The data which informs this model are extremely limited. Equally plausible models with very different properties could easily be constructed.

Gently-dipping or other inclined regional structures are not considered in any of the model variants.

*Treatment of anisotropy and its likely depth-dependence is very limited*

Depth-dependent anisotropy is not investigated except in one of the model variants. This might be a significant factor in explaining the depths to which the localised topographically-controlled flow cells penetrate. Other realistic variants for anisotropy (when also coupled with depth-dependent variation of $K$) can be proposed.

Just one variant was used to investigate effects of depth-dependent anisotropy. In this variant, anisotropy with $K_h = 10K_z$ persists uniformly to a depth of 200 m (40% of the depth to the repository), and continues (though decreasing in magnitude) to 400 m depth (80% of the depth to the repository). This contrasts with the example given in INSITE TRD 04-14 in which $K_h$ is elevated only in the upper 100 m (20% of the depth to the repository).

Depth-dependent anisotropy models based on rock mechanics data for fracture aperture closure under stress, combined with interpreted stress profiles from measurements in boreholes, could give an even more divergent situation from the case considered (Figure 1).

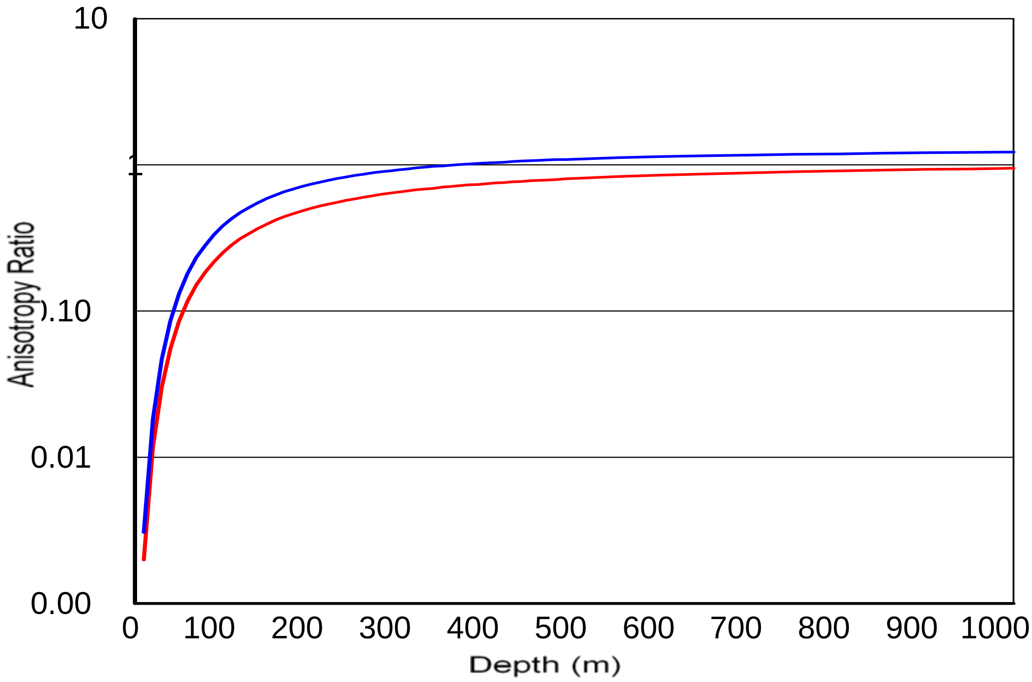


**Figure 1** Predicted anisotropy ratios as a function of depth for vertical vs. horizontal components of hydraulic conductivity in the Laxemar area, calculated based on mean orientations and intensity of the main fracture sets and stress profiles at Laxemar (stress domain I, SKB, 2006) combined with a simple model of fracture transmissivity dependence on effective normal stress (Rutqvist *et al.*, 1998). The red line shows the anisotropy ratio for hydraulic conductivity perpendicular to the maximum principal stress (horizontal, with azimuth 132°) versus in the vertical direction. The red line shows the anisotropy ratio for hydraulic conductivity perpendicular to the minimum horizontal stress (azimuth 42°) versus in the vertical direction. Fracture hydromechanical parameters are taken from Rutqvist *et al.* (1998). For purposes of this example, the mean pole direction of the

subhorizontal fracture set $S_d$ is assumed to be closer to vertical than evaluated at Laxemar (85° *vs.* 65°), considering that nearly-horizontal fractures are poorly characterized on outcrops from which the orientation statistics were developed. Note this first-order calculation does not account for dispersion of fracture orientations around the mean pole of each set.

As previously demonstrated with a very simple 2-D example in TRD 04-14, a model in which anisotropy is concentrated in the uppermost part of the rock (well above the repository horizon, and on a similar scale to local topographic undulations) will reduce the effects of local surface undulations at depth.

*Method for evaluating hill-slope drainage effects is unclear and may contradict past SKB results*

The effect of water-table deviations from the ground surface under local topographic highs (due, *e.g.* to hill-slope drainage) was explored in Case 5J by an ad-hoc method in which, starting from local topographic highs, the prescribed head representing the groundwater table was depressed in surrounding surface cells – apparently for successive rings of surrounding cells – until a local topographic minimum or valley was encountered. Since only very large-scale plots of the adjustments are given (Figure 6-49), it is difficult to know if this method properly simulates the effect of hill-slope drainage.

From the imprecise, qualitative description of the algorithm we are given, it appears that if the starting topographic maximum is a high point on a long and narrow ridge, the water table would only be lowered for points along the ridge which are less than half the ridge width distant. The algorithm should be more clearly specified. Possibly a different approach is needed to support the conclusion that a lower groundwater table under local topographic highs does not significantly affect discharge path length etc.

If represented properly, a depressed water table under local topographic highs should amount essentially to a variant with smoothed topography. The findings from Case 5J appear to contradict SKB's earlier modelling of this region (R-03-23) which concluded that high resolution of topography is very important for the flow field at repository depth. This apparent contradiction should be explained.

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